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Alterations in energy properties of eucalyptus wood and bark subjected to torrefaction: The potential of mass loss as a synthetic indicator

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ABSTRACT

Torrefaction is a mild pyrolysis process (usually up to 300 °C) that changes the chemical and physical properties of biomass. This process is a possible pre-treatment prior to further processes (transport, grinding, combustion, gasification, etc) to generate energy or biofuels. In this study, three eucalyptus wood species and bark were subjected to different torrefaction conditions to determine the alterations in their structural and energy properties. The most severe treatment (280 °C, 5 h) causes mass losses of more than 35%, with severe damage to anatomical structure, and an increase of about 27% in the specific energy content. Bark is more sensitive to heat than wood. Energy yields are always higher than mass yields, thereby demonstrating the benefits of torrefaction in concentrating biomass energy. The overall mass loss is proposed as a relevant parameter to synthesize the effect of torrefaction conditions (temperature and duration). Accordingly, all results are summarised by analytical expressions able to predict the energy properties as a function of the overall mass loss. These expressions are intended to be used in any optimization procedure, from production in the field to the final use.

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1. Introduction

Biomass is an important source of renewable energy, mainly due to its abundance and low cost. In Brazil, sugar cane and wood derivatives are the third and fourth most important energy sources, accounting for 16% and 12% of the internal energy supply, respectively (MME, 2009). However, in order to ensure that their use as energy source is environmental friendly and economically efficient, modification of the biomass is required to improve energy concentration and homogeneity of the biomass properties.

One way of modifying the chemical and physical properties of biomass is to apply torrefaction as a pre-treatment. Torrefaction is a thermal treatment in the temperature range 200–300 °C. The resulting product is intermediate between wood and charcoal, and exhibits certain advantages when compared to the original material (decreased hygroscopicity, dimensional stabilization, increased biological resistance to decay, etc.) (Brito, 1993; Gohar and Guyonet, 1998; Kaila, 1999; Pincelli et al., 2002; Kamdem et al., 2002; Duchez and Guyonnet, 2002; Almeida et al., 2009a). Torrefaction is also recommended as a pre-treatment of biomass prior to gasification, as it decreases the mechanical properties and principally resilience. The torrefied biomass needs less energy for grinding due to partial destruction of the fibrous structure (Bergman et al., 2005; Almeida et al., 2009b).

In studies of heat-induced modifications of wood properties, a strong effect of temperature on the intensity of internal chemical reactions was observed. According to Brito et al. (2008) five important phases are involved. The first phase consists of free and bound water extraction from wood, occurring between room temperature and slightly above the boiling point of water (100 °C at atmospheric pressure). The second phase occurs at temperatures ranging from 100 to around 250 °C and results in the heat-induced transformation of the wood constituents (mainly those containing readily accessible OH-groups), causing irreversible wood degradation. The third phase, which occurs between about 250 and 330 °C, usually involves the total destruction of hemicelluloses. At this stage significant modifications of lignins, namely reduction of the β-O-4 linkage between units and the formation of resistant linkages, referred to as condensed bonds (Nakamura et al., 2008; Rousset et al., 2009). The destruction of cellulose is presumed to occur during the fourth phase, between about 330 and 370 °C. The fifth stage, at temperatures above 350 °C, is when charcoal is produced and the most intense degradation of lignin usually takes place (Guedira, 1988; Vovelle and Mellottee, 1982). Although only the temperature levels are cited above, the combined effect of time × temperature needs to be kept in mind when studying the modification of biomass properties caused by heat.

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American hardwoods subjected to heat treatment showed an accentuated mass loss at temperatures between 200 and 400 °C and a lower cellulose and hemicelluloses resistance compared to lignin (Beall et al., 1974). Another study investigated the behavior of lignin and cellulose when isolated from *Eucalyptus* sp. wood and subjected to a constant temperature of 300 °C. After analyzing the residual content of each component, the authors concluded that cellulose was degraded twice as fast as lignin (Brito and Barrichelo, 1977b).

Given the importance of eucalyptus plantations in Brazil (over 4 million hectares of planted surface, with productivities of about 40 m^3/ha/year) (ABRAF, 2009; Bracelpa, 2007), we investigated the energy properties of eucalyptus woods and bark subjected to different conditions of torrefaction. The biomasses of three economically important species in Brazil were studied: *Eucalyptus grandis, Eucalyptus saligna* and *Corymbia citriodora*.

2. Methods

2.1. Material selection and preparation

Three trees from each species (*E. grandis, E. saligna* and *C. citriodora)* were selected from a 30-year-old plantation of an experimental stand administered by the Forestry Science Department of the University of São Paulo (Brazil), located near Anhembi, São Paulo, Brazil (Lat. 22°48′S, Long. 48°07′W). These species were chosen for their chemical and physical differences (especially *C. citriodora*) and economic importance. Table 1 gives some of their chemical properties.

In the present study, a green, defect-free, quartersawn board of each tree was carefully selected (uniformity of growth rings, straight grain, and absence of knots) and stored at room temperature. The board dimensions were 50 mm (*T*) by 300 mm (*R*) by 650 mm (*L*). Each board was cut into specimens with final dimensions of 15 mm (*T*) by 110 mm (*R*) by 50 mm (*L*). This procedure ensured longitudinal matching and comparable groups for each eucalyptus species. In addition, the thinness reduced the time constant for thermal diffusion into the core to approximately 4 min and thus ensured uniform heat treatment throughout the specimen. Nine adjacent specimens were chosen from each board of *E. grandis* and *E. saligna* to investigate eight torrefaction conditions and keep one sample as reference (or benchmark sample i.e. an untreated specimen). In the case of *C. citriodora,* six comparable groups were prepared, thus five torrefaction conditions and one reference were studied.

Bark samples collected from trees in the experimental stand were also prepared. It was not possible to obtain sufficient bark samples from *C. citriodora* trees. Four adjacent bark samples of final dimensions of 14 mm (*T*) by 50 mm (*R*) by 100 mm (*L*) were prepared. This allowed the study of three torrefaction conditions and one reference. Note that in the present study the internal and external barks were mixed.

Table 1
Chemical composition of the eucalyptus species.

	Chemical composition (%)[a]		
	Acid-insoluble lignin	Cellulose	Hemicelluloses
E. grandis	26.7[b]	–	–
E. saligna	26.5[b]		
	26.3[c]	41.8[c]	31.8[c]
C. citriodora	21.1[b]		
	18.5[c]	51.7[c]	29.8[c]

[a] Dry basis.

[b] Data from Brito and Barrichelo (1977a).

[c] Data from Abreu et al. (2004).

All samples were placed in an oven at 102 °C (±2 °C) for 24 h in order to determine the oven-dry mass before torrefaction. Samples were then kept over silica gel until torrefaction and again, after each torrefaction treatment. The oven-dry mass of the samples after torrefaction was then measured to the nearest 10^{-4} g with a digital balance. Mass loss (*ML*) due to torrefaction was calculated according to the formula:

$$ML = \frac{M_0 - M_t}{M_0}, \tag{1}$$

where, M_0 is the oven-dry mass before torrefaction; M_t is the oven-dry mass after torrefaction.

The average basic density (oven-dry mass to green volume) of the species studied was 576 kg m^{-3} for *E. grandis* wood (coefficient of variation (*CV*) of 9%); 493 kg m^{-3} for *E. grandis* bark (*CV* of 1%), 616 kg m^{-3} for *E. saligna* wood (*CV* of 6%), 459 kg m^{-3} for *E. saligna* internal bark (*CV* of 6%); 279 kg m^{-3} for *E. saligna* external bark (*CV* of 7%) and 792 kg m^{-3} for *C. citriodora* (*CV* of 2%).

2.2. Torrefaction procedure

The oven used for the torrefaction of previously oven-dried specimens was specifically designed for this purpose (hermetically closed, heat rate controlled and continuous acquisition of temperature, oxygen level and sample mass). The torrefaction conditions are presented in Table 2. For the treatments in an inert atmosphere, nitrogen flow was enough to keep the oxygen level, measured at the chamber outlet by an Arelco ZOA 100 sensor, below 1%. More information about the torrefaction procedure is given below:

(a) heating rate of 5 °C/min up to 100 °C; (b) 100 °C for 30 min; (c) heating rate of 5 °C/min until the final treatment temperature is reached then maintained at this level for 1 or 5 h; (c) cooling to 150 °C, in the oven, by opening all the valves.

2.3. Energy properties

Proximate analyses were performed on untreated and torrefied samples according to ABNT-NBR-8112 (Determination of ash, volatile matter and fixed carbon in vegetal charcoal) (ABNT, 1986). Gross calorific value (*GCV*) and net calorific value (*NCV*) of the untreated and torrefied samples were measured according to the ASTM D5865 standard (ASTM, 2007) (dynamic mode at 25 °C) using an adiabatic bomb calorimeter, IKA C2000.

The mass yield (η_M) and energy yield (η_E), when different temperatures and durations of torrefaction were applied to wood and bark, were determined as follows:

$$\text{Mass yield}(\eta_M) = \left(\frac{M_t}{M_0}\right)_{daf} \tag{2}$$

Table 2
Torrefaction conditions applied to the biomass in the present study.

Samples	Torrefaction conditions	
	Residence time (h)	Final temperature/atmosphere
E. grandis wood *E. saligna* wood	1	220 °C/N_2 250 °C/N_2 280 °C/N_2
E. grandis bark *E. saligna* bark	1	220 °C/N_2 250 °C/N_2 280 °C/N_2
E. grandis wood *E. saligna* wood *C. citriodora* wood	5	180 °C/air 220 °C/air 220 °C/N_2 250 °C/N_2 280 °C/N_2

$$\text{Energy yield } (\eta_E) = \eta_M \left(\frac{GCV_t}{GCV_u}\right)_{daf} \tag{3}$$

where: M_0 is the oven-dry mass before torrefaction; M_t is the oven-dry mass after torrefaction; GCV_u is the gross calorific value of untreated samples; GCV_t is the gross calorific value of torrefied samples. *daf*: dry and ash-free basis.

2.4. Statistical analyses

Statistical analyses were conducted using the Statistical Analysis System (SAS) software. Results for untreated and torrefied material were subjected to variance analysis (ANOVA) and the Tukey Test at a 5% probability level, using six replicates for each condition.

3. Results and discussion

The results of mass loss due to torrefaction according to biomass type, residence time and temperature, are presented in Fig. 1. Mass loss is a very effective indicator of the severity of the torrefaction process. It is caused by degradation of the chemical components of wood, especially hemicelluloses which are the components most sensitive to thermal degradation, and produces volatiles. The lower thermal stability of hemicelluloses compared to cellulose is usually explained by the lack of crystallinity of hemicelluloses (Yildiz et al., 2006; Windeisen et al., 2007). Brito et al. (2008), studying the chemical properties of heat-treated *E. saligna*, reported that the sum of arabinose, mannose, galactose and xylose (hemicellulose monomers) decreased from 16.4% (untreated) to 10.2% (180 °C, residence time of 1 h at final temperature). As observed earlier, the combined effect of time × temperature, greatly affects mass loss (Bergman et al., 2005). In our study, the most severe treatment (280 °C, 5 h) caused mass losses of more than 35% in all species and considerable damage to anatomical structure, with several cracks appearing in the most fragile tissues (radial and longitudinal parenchyma) (Fig. 2).

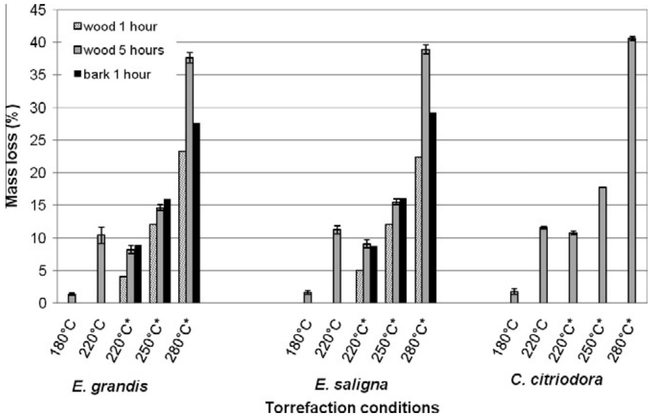


Fig. 1. Mass loss caused by different torrefaction conditions (*indicates treatments in an inert atmosphere, in presence of N_2). Error bars indicate the standard deviation of the mean.

Bark contains a large proportion of parenchyma. According to Quilhó et al. (2000), parenchyma tissues account for 69% of the volume in the secondary phloem of *E. globulus*. Parenchyma cells have very thin walls (pp in Fig. 3) and this fragile anatomic structure is readily prone to degradation by torrefaction compared to wood subjected to the same conditions (Fig. 1). Concerning the chemical composition of the bark, Sakai (2001) showed that *Eucalyptus globulus* bark (bk), as compared to wood (wd), contains slightly less lignin (18.6% bk, 22.3% wd), smaller amounts of cellulose (43.2% bk, 50.1% wd) and similar amounts of pentosan (19.6% bk, 20.5% wd). However, this author reports that significant proportions of hemicelluloses and pectins can be removed during the extraction of tannins with alkaline solutions and that this solubility may adversely affect the accurate analysis of bark components. Fig. 3 shows the anatomical structure of *E. saligna* bark torrefied at 280 °C for 1 h. A large number of cubic crystals can be observed in this figure. Skrifvars et al. (2005) reported the presence of 10–20 μm cubic crystals of calcium oxalate in untreated eucalyptus bark. According to these authors, cubic crystals, most likely calcium carbonate, can still be observed in eucalyptus bark that has been treated at 600 °C for 15 min.

Proximate analyses and calorific values of the biomass samples are presented in Table 3. Statistical analyses did not show any significant differences between untreated wood and wood torrefied at 180 °C, for the majority of the studied properties. Almeida et al. (2009a), studying the physical properties of samples of the same plant materials as tested in the present work, did not observe any modification in shrinkage and hysteresis of wood treated at 180 °C. Also, all the properties of wood and bark torrefied at 280 °C (1 and 5 h) were statistically different from those obtained after other torrefaction conditions.

As expected, an increase in fixed carbon (hence a decrease in volatiles) with increased duration and temperature of torrefaction was observed for all types of biomass studied. An increase in fixed carbon is highly suitable for use in energy production. For example,

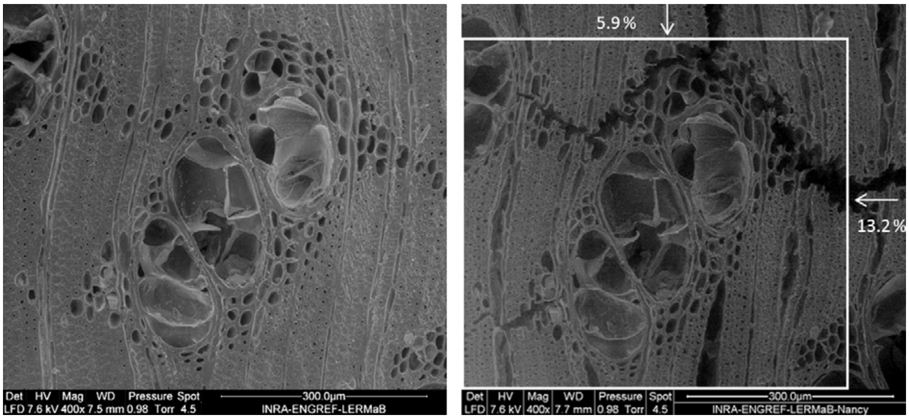
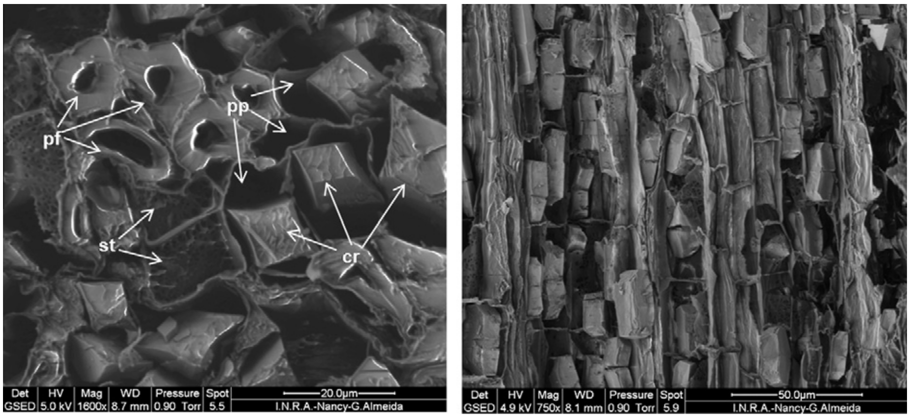

Det HV Mag WD Pressure Spot
LFD 7.6 kV 400x 7.5 mm 0.98 Torr 4.5
300.0μm
INRA-ENGREF-LERMaB
5.9 %
13.2 %
Det HV Mag WD Pressure Spot
LFD 7.6 kV 400x 7.7 mm 0.98 Torr 4.5
300.0μm
INRA-ENGREF-LERMaB-Nancy

Fig. 2. ESEM micrographs of a transversal section of *E. saligna*. Untreated sample (left). Torrefied sample at 280 °C, 5 h (right). White square shows the image dimension before torrefaction, arrows highlight the strength caused by the torrefaction process.


pf
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Det HV Mag WD Pressure Spot
GSED 5.0 kV 1600x 8.7 mm 0.90 Torr 5.5
20.0µm
I.N.R.A.-Nancy-G.Almeida
Det HV Mag WD Pressure Spot
GSED 4.9 kV 750x 8.1 mm 0.90 Torr 5.9
50.0µm
I.N.R.A.-Nancy-G.Almeida

Fig. 3. ESEM micrographs of transversal (left) and radial-longitudinal (right) sections of *E. saligna* bark torrefied at 280 °C, 1 h. pf: phloem fiber; pp: phloem parenchyma, cr: cubic crystals, st: sieve tubes.

Table 3
Proximate analyses and calorific power results.

Torrefaction treatments		Proximate analysis					*GCV* (MJ kg^{-1})		*NCV* (MJ kg^{-1})	
		V.M. (%)[a]		F.C. (%)[a]		Ash (%)[a]				
E. grandis										
Wood	Untreated	83.7	A[b]	16.2	A	0.1	20.0	A	18.7	A
	180 °C air – 5 h	82.0	A	17.7	A	0.3	19.9	A	18.7	A
	220 °C air – 5 h	76.7	B	23.0	B	0.3	20.2	A	18.9	A
	220 °C N_2 – 1 h	77.5	B	22.3	B	0.2	20.8	B	19.5	B
	220 °C N_2 – 5 h	78.5	B	21.4	B	0.1	20.9	B	19.7	B
	250 °C N_2 – 1 h	71.4	C	28.3	C	0.3	21.7	C	20.5	C
	250 °C N_2 – 5 h	75.1	B	24.8	B	0.1	21.5	C	20.3	C
	280 °C N_2 – 1 h	67.5	D	32.3	D	0.2	23.0	D	21.8	D
	280 °C N_2 – 5 h	54.0	E	45.9	E	0.1	25.4	E	24.1	E
Bark	Untreated	60.0	A	34.5	A	5.5	16.9	A	15.6	A
	220 °C N_2 – 1 h	65.7	B	29.5	B	4.8	18.6	B	17.4	B
	250 °C N_2 – 1 h	63.8	B	32.3	C	3.9	18.9	C	17.6	C
	280 °C N_2 – 1 h	53.0	C	42.9	D	4.1	22.6	D	21.3	D
E. saligna										
Wood	Untreated	81.0	A	18.7	A	0.3	19.9	A	18.6	A
	180 °C air – 5 h	79.8	AB	20.0	AB	0.2	20.1	A	18.8	A
	220 °C air – 5 h	75.4	C	24.4	C	0.2	21.0	B	19.7	B
	220 °C N_2 – 1 h	77.1	ABC	22.7	ABC	0.2	20.8	B	19.6	B
	220 °C N_2 – 5 h	76.7	BC	23.1	BC	0.2	20.8	B	19.5	B
	250 °C N_2 – 1 h	72.5	CD	27.2	CD	0.3	21.7	C	20.5	C
	250 °C N_2 – 5 h	73.0	C	26.8	C	0.2	21.5	BC	20.2	BC
	280 °C N_2 – 1 h	67.1	D	32.8	D	0.1	22.6	D	21.8	D
	280 °C N_2 – 5 h	50.5	E	49.4	E	0.1	25.5	E	24.2	E
Bark	untreated	81.6	A	12.2	A	6.2	17.1	A	15.8	A
	220 °C N_2 – 1 h	73.6	B	22.7	B	3.6	17.6	B	16.4	B
	250 °C N_2 – 1 h	65.6	C	29.7	C	4.6	19.5	C	18.2	C
	280 °C N_2 – 1 h	57.9	D	35.6	D	6.5	19.7	D	18.4	D
C. citriodora										
Wood	untreated	83.7	A	16.1	A	0.2	19.8	A	18.6	A
	180 °C air – 5 h	81.9	B	17.9	B	0.2	20.1	A	18.8	A
	220 °C air – 5 h	78.1	C	21.6	C	0.3	21.1	B	19.8	B
	220 °C N_2 – 5 h	78.3	C	21.4	C	0.3	21.0	B	19.8	B
	250 °C N_2 – 5 h	74.6	D	25.1	D	0.3	21.9	C	20.6	C
	280 °C N_2 – 5 h	53.6	E	46.2	E	0.2	25.8	D	24.5	D

V.M.: volatile matter; F.C.: fixed carbon; *GCV*: gross calorific value; *NCV*: net calorific value.

[a] Dry basis.

[b] Means followed by the same letter are not significantly different (Tukey, $\alpha = 5\%$).

in the industrial use of wood charcoal, an increase of 16% in fixed carbon results in a decrease of 4.3 kg of carbon required per ton of pig iron (Assis et al., 1982, cited by Brito, 1993). In the present work, mass loss was used as an indicator of the severity of the torrefaction conditions. Thus, Fig. 4 presents the fixed carbon content as a function of mass loss. Data for charcoal from the three species studied (Brito and Barrichelo, 1977a) are shown in Fig. 4A for comparative purposes. The linear relationship found for all three species ($R^2 = 0.98$), clearly confirms that the overall mass loss is a good indicator of the severity of torrefaction. Note also that the values obtained at 280 °C for 5 h are midway between those of untreated wood and charcoal. Fig. 4B presents the results obtained for two residence times at different temperatures for *E. grandis* and *E. saligna* wood samples. In this figure, the energy concentra-

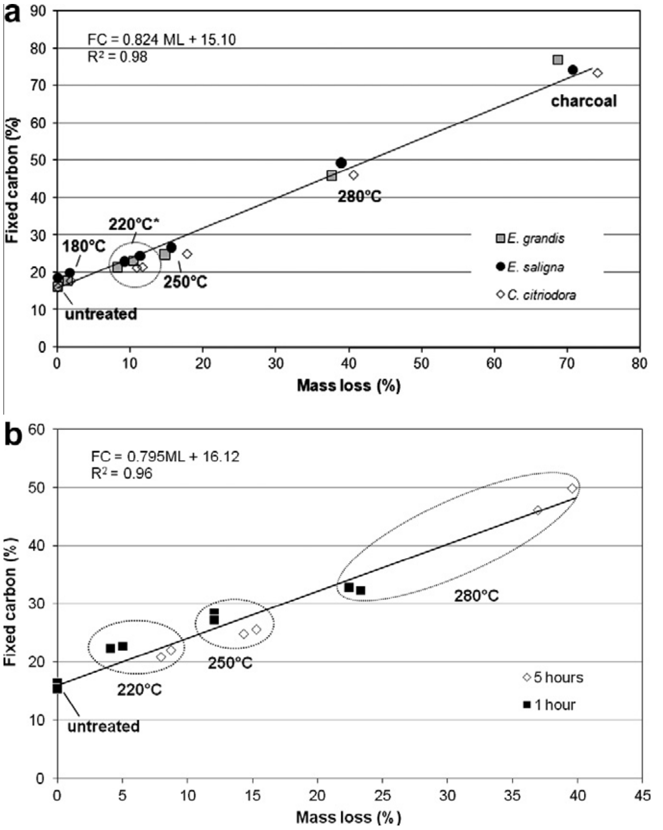

Fig. 4. Fixed carbon as a function of mass loss: (a) samples treated for 5 h at different temperature levels (*220 °C: air and N_2 atmosphere). (b) Samples of *E. grandis* and *E. saligna* treated for 1 and 5 h at three temperature levels (N_2 atmosphere). Charcoal data is taken from Brito and Barrichelo (1977a).

tion as a function of residence time and temperature is linear for the two species (R^2 = 0.96), thus confirming that mass loss is a useful synthetic parameter for determining the effect of torrefaction conditions, namely temperature and duration, on biomass properties. Table 4 presents simple linear regressions of biomass properties as a function of mass loss caused by the torrefaction process.

According to McKendry (2002), the ash content of a biomass affects both the handling and processing costs of the overall biomass energy conversion. The available energy of the fuel is reduced in proportion to the magnitude of the ash content. In combustion processes, where the ash can react to form a 'slag', a liquid phase is formed at elevated temperatures, which can reduce plant throughput and result in increased operating costs. The ash content of the three woods studied is very low (<0.3% dry basis), but much higher in the bark (>3.5% dry basis) and was not affected by torrefaction (Table 3). The high amounts of ash in bark have already been reported in the literature (Brito and Barrichelo, 1978; Ragland et al., 1991; Senelwa and Sims, 1999).

Table 4
Linear regressions of biomass properties as a function of mass loss (*ML*) caused by the torrefaction process.

Properties	Linear regressions	
Volatile matter (VM) (%)	Wood → VM = 83.2 × (1 − 0.009 *ML*)	R^2 = 0.94
	Bark → VM = 72.6 × (1 − 0.008 *ML*)	R^2 = 0.47
Fixed carbon (FC) (%)	Wood → FC = 16.3 × (1 + 0.046 *ML*)	R^2 = 0.95
	Bark → FC = 22.4 × (1 + 0.025 *ML*)	R^2 = 0.47
Gross calorific value (*GCV*) (MJ kg^{-1})	Wood → *GCV* = 19.7 × (1 + 0.006 *ML*)	R^2 = 0.96
	Bark → *GCV* = 16.9 × (1 + 0.009 *ML*)	R^2 = 0.76
Energy yield (η_E)* (%)	Wood → η_E = 100 × (1 − 0.006 *ML*)	R^2 = 0.97
	Bark → η_E = 102 × (1 − 0.006 *ML*)	R^2 = 0.82

Wood: torrefaction conditions → temperature range: 180–280 °C, residence time: 1 and 5 h.
Bark: torrefaction conditions → temperature range: 220–280 °C, residence time: 1 h.
* Energy yield of torrefaction process (Eq. 3).

The calorific value (heat value) of a material is an expression of the energy content that is released when the material is burnt in air. The *GCV* (gross calorific value) is the total energy content released when a fuel is burnt in air, including the latent heat contained in the water vapor and therefore represents the maximum amount of energy potentially recoverable from a given biomass source. In practice, effective use of the latent heat contained in the water vapor is difficult. Depending on the technology used, the *NCV* (net calorific value) may be a more appropriate value for energy purposes (McKendry, 2002). Fig. 5 shows the effect of torrefaction conditions on the calorific values of the different biomass studied. Data for eucalyptus charcoal (Brito and Barrichelo, 1977a; Arantes et al., 2008) have been included in Fig. 5A for comparative purposes. As observed in the analysis of fixed carbon (Fig. 4), gross calorific values as a function of mass loss increase linearly with increased temperature and time of treatment. The most severe treatment (280 °C, 5 h) produced an increase in energy content of about 27% in all three species. The energy contents of wood are always higher than those of bark.

Mass and energy yields from the untreated to torrefied biomass are strongly dependent on the torrefaction temperature, residence time and biomass type (wood or bark) (Fig. 6). Bergman et al. (2005) observed a distinct dependency of mass yield on the torrefaction temperature, and showed that above 250 °C the mass yield of biomass drops exponentially. In the present work, eucalyptus

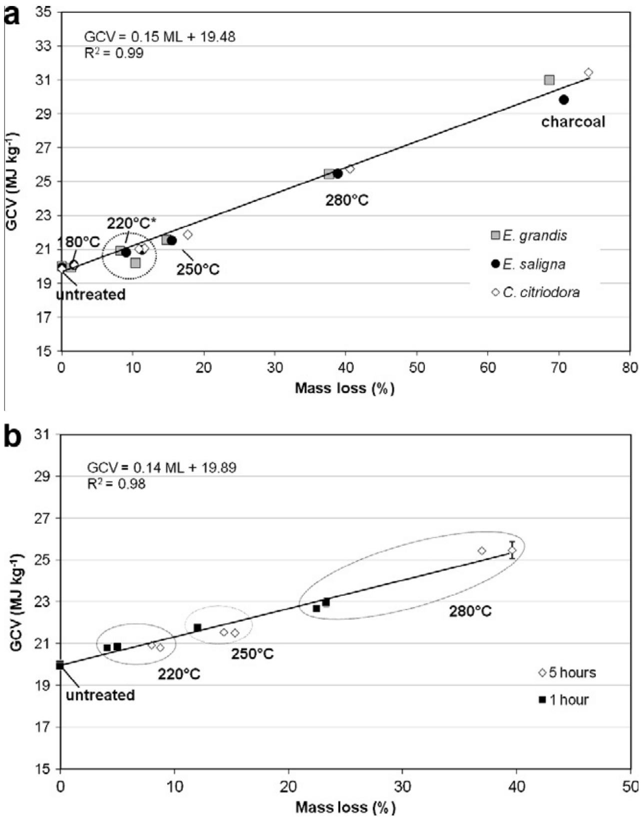

Fig. 5. Gross calorific value as a function of mass loss: (a) samples treated for 5 h at different temperature levels (*220 °C: air and N_2 atmosphere). (b) Samples of *E. grandis* and *E. saligna* treated for 1 and 5 h at three temperature levels (N_2 atmosphere). Charcoal data is taken from Brito and Barrichelo (1977a); Arantes et al. (2008).

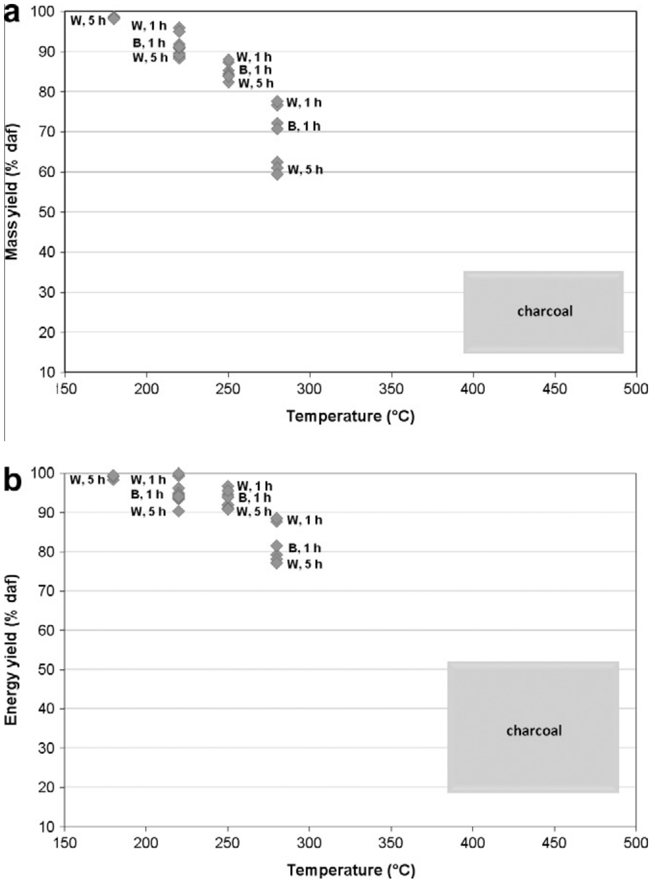

Fig. 6. Mass yield and energy yield of wood (*W*) and bark (*B*) heat treated under different conditions. Charcoal data is taken from Schenkel et al. (1997).

woods treated at 280 °C (5 h) lost about 40% of their mass, compared to 23% in woods treated for 1 h at the same temperature.

Energy loss is the most relevant parameter if the biomass is intended for energy uses. Due to the increased calorific value with torrefaction, which denotes an enhancement of product quality compared to that of the untreated biomass, the energy loss is lower than the mass loss. For example, eucalyptus woods treated at 280 °C for 1 h lost only 12% of the initial energy content compared to 23% of mass loss. The difference between the energy yield and the mass yield increases with the increase in temperature and duration of torrefaction. For example, the differences between energy yields and mass yields for eucalyptus woods were about 17% (280 °C, 5 h) and 11% (280 °C, 1 h), respectively. Bark exhibited slightly higher energy losses than wood (Fig. 6b). Svoboda et al. (2009) observed that approximately 10–20% of the energy content was lost in the production of torrefied willow wood. They observed a moderately higher energy loss for straw and grass.

Mass and energy yields from charcoal depend on the carbonization process and species used. Schenkel et al. (1997) reported a large range of yields and these data have been included in Fig. 6 for comparison. This figure clearly shows the benefits of torrefied biomass on concentrating energy, and prevents the higher losses of productivity and energy that would result from carbonization.

4. Conclusion

In this work, we measured the energy properties of three eucalyptus species and bark before and after various torrefaction conditions. Our results prove that the torrefaction parameters (temperature levels and durations) can be tune to obtain various products, ranging from native biomass to charcoal. The analysis of the whole data set proves that the mass loss is an excellent indicator of the treatment intensity. Therefore, all results are summarised by analytical expressions able to predict the energy properties as a function of the overall mass loss. These expressions are intended to be used in any decision-making process, including the overall optimization of the transformation chain, from production in the field to the final need.

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